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Development of temperature and humidity independent control (THIC) air-conditioning systems in China—A review

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ABSTRACT

A temperature and humidity independent control (THIC) system is a way to regulate indoor temperature and humidity separately through different approaches. Because of this distinction, THIC air-conditioning systems can satisfy the adjustment requirements of indoor temperature and humidity better than conventional systems can, and they show significant potential for energy conservation. In the past ten years, rapid improvements have been achieved in both theoretical research and the development of equipment related to THIC systems, and more and more applications are being put into use in non-residential buildings in China. This paper focuses on the development of THIC systems in China and reviews recent achievements and progress related to the main devices used for temperature and humidity control, including outdoor air handling dehumidification processors, sensible heat terminals, and high-temperature cooling sources. The energy performance of THIC systems is examined based on an analysis of established applications. Both the performance of key components and the energy consumption of entire systems indicate that THIC systems result in significant improvements in energy performance compared to conventional systems. Developmental trends and recommendations about design methodology, ways to improve the performance of handling devices, and feedback from applications of THIC systems are also discussed.

Contents

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1. Introduction

Building energy consumption accounts for about 23% of the total energy consumed in China [1], and this proportion is predicted to increase as both the economy and society as a whole continue to develop rapidly. It is of great strategic significance to promote energy saving in buildings and pursue emission reduction. At the same time, non-residential buildings are developing very quickly in China. There was a total of approximately 7.8 billion m^2 of non-residential buildings in China in 2008, and about 4–5 million m^2 of new buildings are being built every year [1,2]. The energy consumption of air-conditioning systems represents a large proportion of the total energy consumption of non-residential buildings, usually 20–60% [3,4]. Thus, decreasing the energy consumption of air-conditioning systems is one of the main ways to save energy in non-residential buildings.

In conventional air-conditioning systems, the indoor sensible load and latent (moisture) load are handled by chilled water at the same time [5]. In other words, condensing dehumidification is used to regulate both indoor temperature and humidity. In fact, the required temperature of the cooling source is lower than the indoor air temperature and the dew bulb temperature in order to control the indoor temperature and humidity, respectively. Moreover, the sensible load is usually larger than the latent load, but even though the sensible load can be removed by a cooling source with a relatively higher temperature, it is typically handled by the same lower-temperature cooling source together with dehumidification, which leads to significant energy loss. Furthermore, conventional methods cannot effectively accommodate the large variances in sensible or latent loads in many buildings, resulting in indoor temperatures or moisture levels that exceed inhabitants' comfort ranges. Reheating is a possible solution in order to avoid such problems, but it can lead to unnecessary energy dissipation. Many researchers have attempted to address the shortcomings of conventional air-conditioning systems, and numerous solutions have been proposed. Regulating indoor temperature and humidity separately is one promising method, and this approach has becoming increasingly popular in recent years.

Dedicated outdoor air systems (DOAS) [6] have been proposed in the United States, and different devices have been adopted for humidity control and temperature control. These systems connect low-temperature air supply devices and sensible cooling terminals where the outdoor air is processed to a sufficiently dry state to satisfy the requirement of removing the indoor latent load [7]. DOAS conform to the ASHRAE standard for fresh air [8] in an energy-efficient manner, and operating cost savings can be achieved at the same time as significant improvements in indoor air quality and thermal comfort. DOAS are developing quickly, and several applications have been investigated [9,10]. However, conventional chillers are adopted in DOAS for both humidity control and temperature control; no special chillers supplying higher-temperature chilled water have been developed for temperature control, limiting further improvements in energy performance. Interestingly, radiant cooling terminals, which represent an effective way to extract sensible heat for temperature control, are appearing in systems in Europe [11,12]. If chilled water of an appropriate temperature is imported into the radiant terminals, indoor sensible heat can be extracted through radiant heat exchange and natural convection. Radiant terminals have become popular in Europe because a suite of terminals can be used for both cooling and heating, and the outdoor condition in most areas of Europe is dry enough to alleviate any concern about condensation on the surface of the radiant terminals in summer. Radiant terminals have been shown to be a good choice for low-temperature heating systems and high-temperature cooling systems, especially in research on low exergy systems in the Annexes [13–15] of the International Energy Agency's (IEA) Implementing Agreement on Energy Conservation in Buildings and Community Systems (ECBCS). In contrast to the dry outdoor climate in most parts of Europe, where there is little risk of condensation in radiant cooling, the outdoor air is humid in many areas of China. This means that if radiant cooling is adopted for temperature control in China, humidity control will be a more challenging task than it is in Europe [16].

Temperature and humidity independent control (THIC) air-conditioning systems, which consist of temperature control and humidity control subsystems, were first developed in China [17]. The basic idea of the THIC system is to regulate indoor temperature and humidity separately. A high-temperature cooling source is utilized for temperature control, and processed air with a relatively low humidity ratio is supplied into indoor spaces for humidity control. With the support of the 11th Five-year National Science and Technology Support Program of China (2006–2010), a number of organizations, including design institutes, research and development institutions, and equipment manufacturers, were involved in collaborative research and development of THIC systems. Newly developed handling devices and practical applications of THIC systems have been continuously promoted in recent years. In the early stages, THIC systems consisted of devices commonly used for conventional systems. Now, there are equipment components that are made especially for THIC systems, including high-temperature water chillers, dry fan coil units (FCUs), liquid desiccant outdoor air dehumidifiers, etc. Since 2006, almost 4 million m^2 of non-residential buildings have adopted THIC systems. With the rapid development of its particular devices and applications, the THIC system has been included in design handbooks and standards in China [18,19].

This paper focuses on the progress of THIC systems in China. Recent developments related to high-temperature water chillers, outdoor air handling devices, and sensible terminals are reviewed, and the energy performance of THIC systems in typical applications is investigated.

2. Operating principle of THIC systems

2.1. Independent control of indoor humidity and operating principle of THIC systems

The total cooling load of a building [20] includes both the sensible load from the outdoor air, building envelope, occupants, devices, lighting, etc., and the latent load (moisture load) from the outdoor air, indoor occupants, indoor wet surfaces, etc., as shown in Fig. 1. The main element of the indoor latent load in common non-residential buildings, such as office buildings, hotels, and shopping malls, is from occupants. In most cases, the sensible load accounts for a greater proportion of the total load than the latent load does. Air-conditioning systems are primarily responsible for

Nomenclature

G	required flow rate of outdoor air (m^3/h)
M	indoor moisture generation (g/h)
P	power consumption (kW)
Q	cooling capacity (kW)
T	temperature (°C)

Greek symbols

ρ	density of air (kg/m^3)
ω	humidity ratio (g/kg)
$\Delta\omega$	humidity removal between outdoor air and supplied air (g/kg)

Subscripts

a	air
CH	chiller
CT	cooling tower
CTP	cooling water pump
CWP	chilled water pump
db	dry-bulb temperature
e	evaporation
FAN	fan
FCU	fan coil unit
in	inlet
N	indoor return air
OAP	outdoor air processor using liquid desiccant
out	outlet
S	supplied outdoor air
HUM	humidity control subsystem of THIC system
SYS	total THIC system
TEMP	temperature control subsystem of THIC system
w	water
wb	wet-bulb temperature

regulating the indoor temperature, indoor humidity, and air quality, and the latter two tasks can be accomplished by introducing dried outdoor air to remove the extra indoor moisture and transfer indoor pollutants to the outdoor environment. If the handled outdoor air assumes the responsibility of removing the total moisture load in buildings, the required humidity ratio of the supplied outdoor air will be

$$\omega_S = \omega_N - \frac{M}{\rho G} \quad (1)$$

where ω_S and ω_N represent the humidity ratio of the supplied outdoor air and indoor air, respectively (g/kg), M is the indoor moisture generation (g/h), ρ is the density of the air (kg/m^3), and G is the required flow rate of the outdoor air (m^3/h).

If the supplied outdoor air is utilized to remove the total indoor latent load in buildings, its humidity ratio should be lower than that of the indoor condition, as indicated by Eq. (1), and the difference is the requirement to remove the indoor moisture load. When the indoor condition is 26 °C with 60% relative humidity (ω_N=12.6 g/kg), the required humidity ratio of the supplied air (ω_S) to remove the moisture load of occupants is 9.8 g/kg when the flow rate of the outdoor air per person is 30 m^3/h.

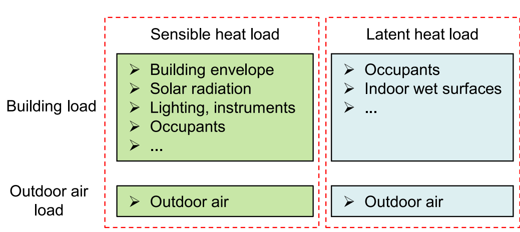


Fig. 1. Load configuration of the air-conditioning systems.

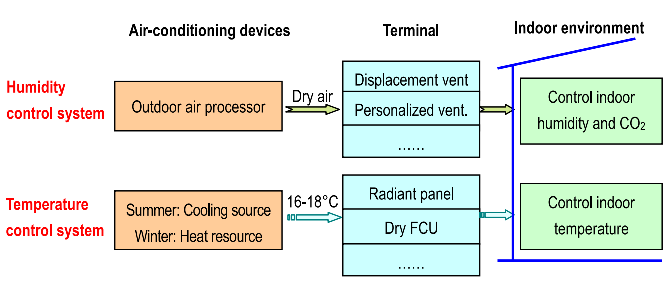


Fig. 2. Operating principle of the THIC air-conditioning system.

Looking at the building load configuration in Fig. 1, the variance of the indoor sensible load of occupants is proportional to the number of occupants. As the flow rate of the outdoor air is also proportional to the number of occupants, the supplied outdoor air can be used to remove the indoor sensible load of occupants to accommodate the variance of the indoor sensible load. For example, when the indoor condition is 26 °C, the required temperature of the supplied air is 20.4 °C if the flow rate of the outdoor air per person is 30 m^3/h.

Fig. 2 illustrates the operating principle of a THIC air-conditioning system based on independent control of the indoor humidity. It includes an outdoor air handling subsystem and a relatively high-temperature cooling source subsystem, which can regulate the indoor humidity and temperature separately. In the humidity control subsystem, the handled outdoor air assumes the two main tasks of the air-conditioning system, i.e., supplying enough outdoor air to meet the requirements of indoor air quality and providing sufficiently dry outdoor air to remove the total moisture load in the building in order to control the indoor humidity. Another subsystem with a relatively higher-temperature cooling source can be utilized to control the indoor temperature. In order to reduce the

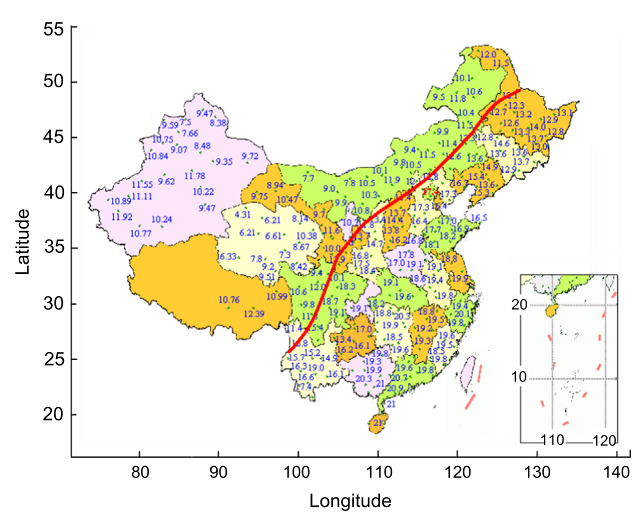


Fig. 3. Monthly average outdoor air humidity ratio during the most humid month in China (g/kg).

energy consumption of the transportation system, either water or refrigerant is the recommended fluid medium in the temperature control subsystem.

2.2. Requirements of key handling devices in THIC systems

Various kinds of devices can be combined together to form a THIC system [17], and different natural resources can be utilized for different climate regions. The outdoor conditions in Chinese cities vary tremendously, and Fig. 3 shows the monthly average outdoor air humidity ratio during the most humid month [21]. Based on the average humidity ratio of 12 g/kg, climates can be classified as either humid climates or dry outdoor climates. In northwestern China, the outdoor climate is quite dry, and the main task of outdoor air handling systems is to cool the outdoor air rather than to dehumidify it. In dry areas, direct or indirect evaporative cooling technology can be utilized in THIC systems to cool the outdoor air and to produce high-temperature chilled water. For example, because the outdoor air is already sufficiently dry in the northwest of China, the indirect evaporative cooling method can produce 16–18 °C chilled water with high energy efficiency [17]. However, in southeastern China, the outdoor climate is humid, and the main task of outdoor air handling systems is to dehumidify it efficiently.

This paper focuses on THIC systems in humid areas, and Fig. 4 (a) illustrates the operating schematic of a THIC system utilizing desiccant dehumidification. The air handling process in this THIC system is illustrated in Fig. 4(b), with an outdoor air processor and dry FCUs taken as examples. In THIC systems, the requirements for outdoor air handling processes, high-temperature cooling sources, and indoor terminals are different from those of conventional systems.

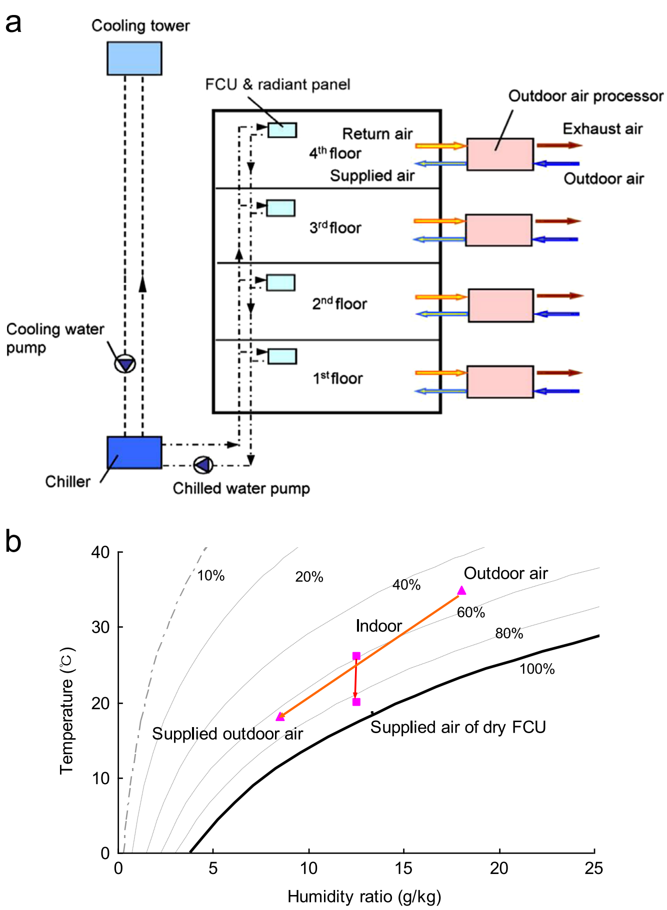


Fig. 4. The THIC air-conditioning system: (a) a typical outdoor air system with FCUs; (b) psychrometric chart of the air handling process.

2.2.1. Requirements for the outdoor air handling process

In humid regions, the outdoor air is hot and humid in summer, and it has to be sufficiently dehumidified before being supplied to the indoor environment to control the indoor humidity. Dehumidification is a more difficult task than cooling. Compared to conventional systems, the outdoor air handling devices in THIC systems have to dehumidify the air to a drier state. Table 1 compares the required humidity removal of conventional systems to that of THIC systems in typical cities. As indicated by this table, the outdoor air in conventional systems only has to be dehumidified to the same humidity ratio as the indoor environment, but in THIC systems, a higher humidity removal is required, about 30–40% higher than conventional systems in the design condition. This means that dehumidification is more difficult in THIC systems [17], so the realization of an efficient outdoor air handling process would significantly improve the system performance of THIC systems.

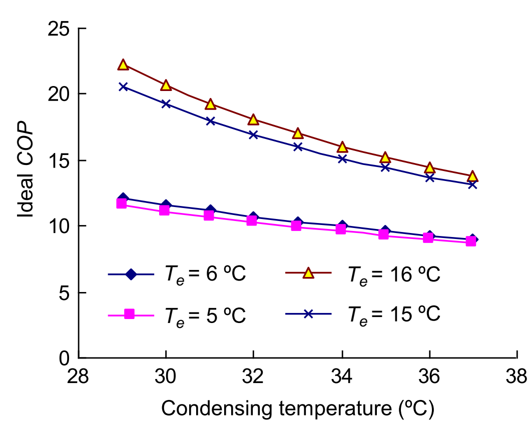


Fig. 5. The ideal *COP* of chillers with different evaporating temperatures.

Table 1
Comparison of required humidity removals of conventional systems and THIC systems in typical cities.

City	Outdoor air design parameters			Indoor ω (g/kg)	Required ω_S of THIC systems (g/kg)	Required $\Delta\omega$ (g/kg)		Increase of $\Delta\omega$ (%)
	T_{db} (°C)	T_{wb} (°C)	ω (g/kg)			Conventional systems	THIC systems	
Beijing	33.2	26.4	19.3	12.6[a]	9.8[b]	6.7	9.5	42
Shanghai	34.0	28.2	22.1			9.5	12.3	30
Wuhan	35.2	28.2	21.7			9.1	11.9	31
Guangzhou	33.5	27.7	21.4			8.8	11.6	32

[a] Indoor condition is 26 °C and 60% relative humidity.
[b] The supplied air is only used to remove the moisture load of occupants; the air flow rate for one person is 30 m^3/h.

Table 2
Comparison of compression ratios of conventional chillers and high-temperature chillers [23].

Refrigerant	Condensing parameters		Conventional chillers			High-temperature chillers		
	Temperature (°C)	Pressure (Mpa)	Evaporating temperature (°C)	Evaporating pressure (Mpa)	Compression ratio	Evaporating temperature (°C)	Evaporating pressure (Mpa)	Compression ratio
R22	36–40	1.39–1.53	3–5	0.55–0.58	2.3–2.8	14–16	0.77–0.81	1.7–2.0
R134a		0.91–1.02		0.32–0.35	2.6–3.1		0.47–0.51	1.8–2.2

For the humidity subsystem in a THIC system, condensing dehumidification or desiccant dehumidification can be adopted to dehumidify the outdoor air. The condensing method is usually utilized to handle the outdoor air in conventional systems, so it could also be used for dehumidification in THIC systems. However, the handled air state is almost saturated if the condensing method is adopted, and air temperature is usually too low to supply indoor air if the humidity ratio is satisfied. As a result, reheating by indoor exhaust air, outdoor air, or other means is needed. In addition to the condensing method, dehumidification methods that use liquid desiccant or solid desiccant can satisfy the dehumidification requirement for outdoor air in THIC systems. Adopting liquid or solid desiccants avoids the need for reheating, and these methods utilize waste heat to a greater extent than the condensing method. Thus, utilizing desiccant is a feasible way to handle the outdoor air in a THIC system.

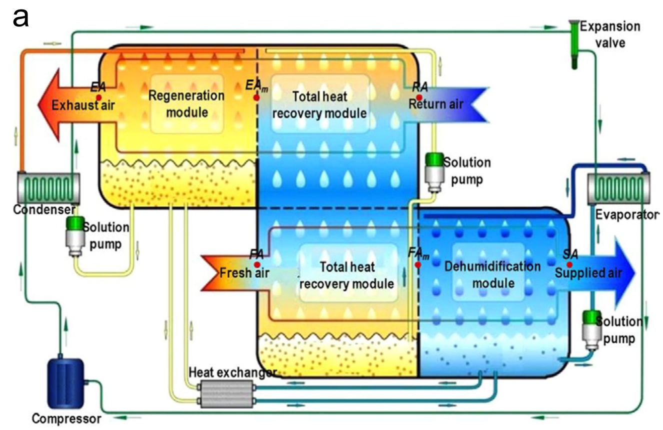
2.2.2. *Requirements for indoor terminals*

In THIC systems, because the indoor temperature can be regulated by a high-temperature cooling source, the indoor terminals will be quite different from those in conventional systems. There are two types of sensible heat terminals that are typically used for temperature control in THIC systems: dry FCUs (fan coil units) and radiant terminals. Radiant panels are an appropriate option for the indoor temperature control subsystem, and they do not rely on the energy consumption of indoor fans. As there are no differences between the radiant panels utilized in THIC systems and those utilized in other devices, a detailed analysis of radiant terminals in THIC systems is not included in this review.

In conventional systems, FCUs work under wet conditions (i.e., there is condensing water in the operating process). If FCUs are utilized only for temperature control, the temperature of the supplied chilled water increases and the FCUs work under dry conditions. However, at first, no dry FCUs were developed specifically for THIC systems, so conventional wet FCUs were used for temperature control under dry conditions. Zhang [22] constructed a THIC system that adopted conventional wet FCUs as the indoor temperature control terminals, but the performance of the wet FCUs working under dry conditions was not as good as expected. Thus, dry FCUs need to be developed specifically for THIC systems.

2.2.3. *Requirements for high-temperature cooling sources*

As for the temperature control subsystem, natural cooling sources can be utilized directly as high-temperature cooling sources since the required temperature of the cooling source increases from 7 °C in conventional systems to about 16–18 °C in THIC systems. For example, phreatic water or ground source heat exchangers with the appropriate temperature can be used directly for temperature control (if the hydrogeologic conditions allow). If no natural cooling sources are available, mechanical chillers are needed to satisfy the requirement for high-temperature chilled water in buildings. The evaporating temperature of the high-temperature chillers in THIC systems is significantly higher than



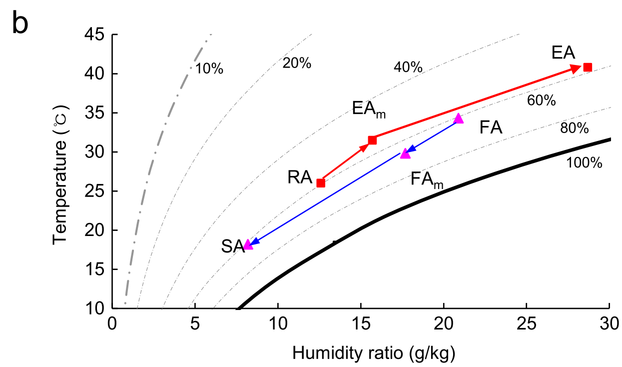


Fig. 6. Heat pump-driven liquid desiccant outdoor air handling processor: (a) operating principle; and (b) psychrometric chart of the air handling process.

that of conventional chillers, and theoretically, the coefficient of performance (*COP*) much will be much higher as a result of utilizing relatively higher-temperature cooling sources. Fig. 5 shows the ideal *COP* of high temperature chillers and conventional chillers based on the second law of thermodynamics.

However, in contrast to conventional water chillers that produce 7 °C chilled water, the defining characteristic of high-temperature chillers is that they have to operate with a small compression ratio when producing 16–18 °C chilled water. Table 2 compares the compression ratios of conventional water chillers and high-temperature water chillers [23]. With the same condensing pressure, the compression ratio of the high-temperature chillers in THIC systems is only about 70% of that of conventional chillers due to the remarkable increase in evaporating pressure. This significant decrease in compression ratio helps to improve the ideal *COP* of high-temperature chillers, and it is clear that conventional chillers could not be adopted directly for the production of high-temperature chilled water. The specific volume of refrigerant decreases as temperature increases, and the specific volumes of R22 at 5 °C (conventional evaporating temperature) and 15 °C (evaporating temperature for THIC systems) are 0.0404 m^3/kg and 0.0300 m^3/kg, respectively. For compressors with a fixed suction volume, such as scroll compressors and screw compressors, the decrease of specific

Table 3
Performance of a heat pump-driven liquid desiccant outdoor air processor with heat recovery [25].

Testing condition	Outdoor air	Supply air	Cooling capacity (kW)	Compressor power (kW)	Pump power (kW)	*COP*
Rated load condition	36.0 °C, 25.8 g/kg	17.3 °C, 9.1 g/kg	82.7	14.6	1.9	5.0
Part-load condition	30.0 °C, 21.6 g/kg	17.3 °C, 9.6 g/kg	42.7	5.8	1.4	5.7

Table 4
Performance comparison of a conventional wet FCU working under dry conditions and a newly developed dry FCU (type: FP-68).

FCU type	Air inlet		$T_{w,in}$ (°C)	$T_{w,out}$ (°C)	Air outlet		Fan power (W)	Cooling capacity (W/(m^3/h))
	$T_{a,db}$ (°C)	$T_{a,wb}$ (°C)			$T_{a,db}$ (°C)	$T_{a,wb}$ (°C)		
Conventional FCU	27	19.5	7	12	14.5	13.6	61	6.0
Conventional FCU	26	18.7	16	21	22.2	17.4	63	1.3
Dry FCU	26	18.7	16	21	19.8	16.6	61	2.0

Table 5
Performance comparison of dry FCUs and conventional wet FCUs according to Chinese national standards.

Type	Rated flow rate (m^3/h)	Input power (W)	Performance of conventional wet FCUs [30][a]			Performance of dry FCUs [28][b]		
			Cooling capacity (W)	TC_{FCU} (W/W)	Cooling capacity per unit flow rate (W/(m^3/h))	Cooling capacity (W)	TC_{FCU} (W/W)	Cooling capacity per unit flow rate (W/(m^3/h))
FP-34	340	37	1800	49	5.3	680	18	2.0
FP-68	680	62	3600	58	5.3	1360	22	2.0
FP-102	1020	96	5400	56	5.3	2040	21	2.0
FP-136	1360	134	7200	54	5.3	2720	20	2.0
FP-170	1700	152	9000	59	5.3	3400	22	2.0
FP-238	2380	228	12,600	55	5.3	4760	21	2.0

[a] Chilled water = 7.0 °C/12.0 °C, indoor condition = 27.0 °C, and wet bulb = 19.5 °C.
[b] Chilled water = 16.0 °C/21.0 °C, indoor condition = 26.0 °C, and wet bulb = 18.7 °C.

volume results in an increase of the mass flow rate of sucked refrigerant, thereby increasing the cooling capacity. However, this also results in an imbalance between supply and demand, and it could even cause an overload of the motor.

At the same time, the operating pressure difference before and after throttling decreases significantly under a high evaporating temperature; therefore, a redesigned throttle is needed for high-temperature water chillers. In addition, if there is oil in the refrigeration cycle, the operating condition for oil return will be quite difficult compared to conventional chillers. Thus, with the increase of evaporating temperature and the decrease of compression ratio, significant changes in operating conditions emerge, resulting in new demands for high-temperature water chillers. New optimization designs are required for compressors and other components, and new chillers have to be developed specifically for THIC systems.

The next section will review recent developments with regard to outdoor air handling devices, sensible terminals, and high-temperature cooling sources in THIC systems in the humid regions of China.

3. Development of key components of THIC systems

3.1. Outdoor air handling processors

Outdoor air handling units that utilize liquid desiccant are a feasible choice for humidity control in THIC systems, and numerous buildings have adopted liquid desiccant-based THIC systems in China. According to different heat sources for desiccant regeneration, there are two main types of air processors: low-grade heat-driven devices (i.e., by hot water at a temperature greater than 70 °C) and heat pump-driven devices (i.e., by desiccant regeneration by exhaust heat from the condenser of the heat pump). The heat pump-driven type is the most widely used type of air processor utilizing liquid desiccant in China, and almost 90% of the outdoor air processors in practice that use liquid desiccant are driven by heat pumps.

Li et al. [24] proposed a heat pump-driven liquid desiccant outdoor air processor with a total heat recovery module, which was successfully utilized in a hospital for indoor humidity control. The experimental tests showed that the *COP* of the processor was as high as 6.0 in experimental summer conditions, and hour-by-hour simulation based on the climate data of Beijing showed that the average *COP* was 5.3. Liu et al. [25] tested the performance of a heat pump-driven liquid desiccant outdoor air processor with a two-stage dehumidifier and regenerator. The operating principle and air handling process are illustrated in Fig. 6(a) and (b), respectively. The device consists of a two-stage total heat recovery module and a two-stage air handling module. The heat recovery module is utilized for total heat recovery between indoor return air and fresh air. In the air handling module, fresh air flows through the dehumidifier after heat recovery and is dehumidified to a required humidity ratio. Meanwhile, the return air is used for desiccant regeneration and exhausted with moisture from the diluted solution. In the desiccant cycle, diluted solution flowing out of the dehumidifier is heated by the condensing heat of the heat pump module and then concentrated in the regenerator. There is also a heat exchanger for heat recovery between the cycling solutions of the dehumidifier and regenerator. Then, the concentrated solution is cooled by the evaporator of the heat pump module before flowing into the dehumidifier. Table 3 shows the operating performance of an outdoor air processor with a flow

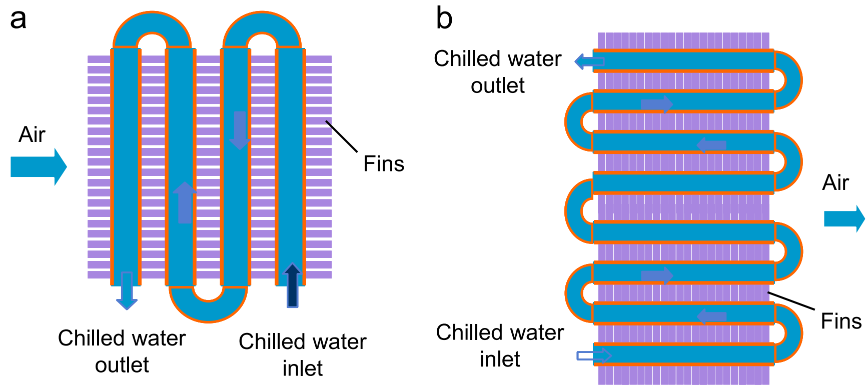


Fig. 7. Typical flow arrangements for an FCU: (a) quasi-counter flow pattern; and (b) a cross flow pattern.

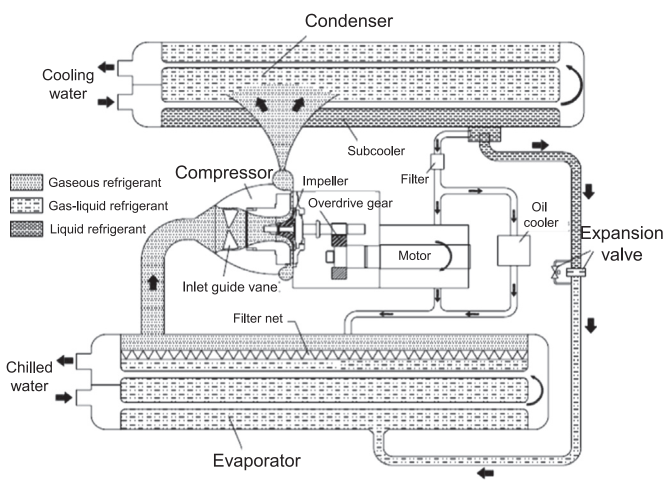


Fig. 8. The refrigeration cycle of a centrifugal high-temperature water chiller by Gree Electric Appliances, Inc. of Zhuhai [31].

rate of 4000 m^3/h under rated load and part-load conditions, where the temperature and humidity parameters of the return air are 26 °C and 12.6 g/kg, respectively. These results demonstrate that the energy performance of this two-stage heat pump-driven liquid desiccant outdoor air processor is quite good based on appropriate supply air parameters.

3.2. Indoor sensible terminals

Due to the temperature increase of the supplied chilled water, the temperature difference between the water and the indoor temperature in THIC systems decreases considerably compared to conventional systems. Taking an indoor temperature of 26 °C as an example, the temperature difference is 8 °C in THIC systems when the surface temperature of the dry FCUs is 18 °C; in conventional systems, the temperature difference can be as high as 18 °C with a surface temperature of 8 °C. In other words, the temperature difference in THIC systems is less than half of that in conventional systems. This decrease in temperature difference for convection heat transfer leads to a significant decline in the heat exchange for unit FCU area.

FCUs working under dry conditions have been developed specifically for THIC systems in China. Tian et al. [26] compared the performances of a conventional wet FCU working under dry conditions and a newly developed dry FCU, as shown in Table 4. It can be seen that adopting conventional wet FCUs under dry conditions is not very suitable, and the performance of the newly developed dry FCUs is superior to that of the conventional FCUs to a certain extent. Zhang et al. [27] introduced the normal conditions in the standard that specifies the basic performance of dry FCUs [28] for THIC systems in China, and established a performance-testing model. The following subsection provides a detailed comparison of the performance of conventional wet FCUs to that of the newly developed dry FCUs.

To extract the same sensible load, a greater heat transfer area or air volume is needed for dry FCUs than for wet FCUs. The energy performance of FCUs is evaluated using the transportation coefficient of FCUs (TC_{FCU}), defined as cooling capacity divided by fan power [29]. TC_{FCU} of dry FCUs will be much lower than that of conventional wet FCUs if a similar configuration is designed. Table 5 compares the TC_{FCU} of dry FCUs to that of conventional wet FCUs. The TC_{FCU} of the newly developed dry FCUs is approximately 22, while the TC_{FCU} of conventional FCUs is over 50. This large performance discrepancy is due to the decrease in temperature difference between the indoor air and the supplied chilled water in THIC systems. As the operating conditions are different for dry and wet FCUs, the key issue for developing dry FCUs is to pursue an efficient heat transfer process under a lower temperature difference. For example, a smaller interval of fins and a thinner pipe diameter are recommended to enhance heat transfer. Operating in dry conditions means that there is no condensing water, which helps to form a new construction that differs from conventional wet FCUs. Fig. 7(a) illustrates the quasi-counter flow arrangement of a dry FCU, which is different from the common cross flow pattern of a wet FCU, shown in Fig. 7(b). In brief, the energy performance of existing dry FCUs is not satisfactory, and further efforts are still needed in order to improve performance.

3.3. High-temperature cooling sources

Fig. 8 illustrates the refrigeration cycle of a centrifugal high-temperature water chiller using R134a for THIC systems developed by Gree Electric Appliances, Inc. of Zhuhai [31]. Throughout the development of high-temperature centrifugal compressors, the impellers have been redesigned (including the number of vanes, outlet width, and vane curve) to improve adiabatic efficiency [32]. At the same time, diffusers with variable cross-sections and guide vanes are combined effectively to ensure high efficiency in part-load conditions [33]. Lubricating oil is cooled adequately, and the oil return process is not influenced by the suction velocity or the pressure difference, ensuring the reliability of oil return. The throttle has been redesigned to accommodate a smaller operating pressure difference compared to conventional chillers. As for the control strategy, the surge region and transition region are divided, and efforts have been taken to prevent the compressor from working in the surge region.

Table 6
Performance of centrifugal chillers with a relatively higher temperature of chilled water.

Outlet temperature of chilled water (°C)	Flow rate of chilled water (m^3/h)	Inlet temperature of cooling water (°C)	Flow rate of cooling water (m^3/h)	Cooling capacity (kW)	Input power (kW)	COP_{CH}	Comments
Conventional chiller							
7.0	688	30.0	860	3963	683	5.78	
16.0	688	30.0	860	4088	601	6.80	
18.0	688	30.0	860	4095	581	7.05	
Newly developed chiller							
16.0	688	30.0	860	3826	446	8.58	100% Load
16.0	688	26.0	860	2953	292	10.10	75% Load
16.0	688	23.0	860	2034	214	9.52	50% Load
16.0	688	19.0	860	1123	163	6.88	25% Load
18.0	688	30.0	860	3966	432	9.18	100% Load
18.0	688	26.0	860	3046	302	10.10	75% Load
18.0	688	23.0	860	1978	202	9.80	50% Load
18.0	688	19.0	860	1322	157	8.41	25% Load

Table 7
Performance of each component in conventional air-conditioning systems according to Chinese national standards.

Component	Power consumption	Definition of *COP*	Reference value of *COP*		Source
			Conventional systems	THIC systems	
Chiller	P_{CH}	$COP_{CH}=\frac{Q}{P_{CH}}$	5.1–5.6	8.5 (16°C)	GB 19577–2004 [34]
Chilled water pump	P_{CWP}	$TC_{CWP}=\frac{Q}{P_{CWP}}$	41.5	41.5	GB 50189–2005 [35]
Cooling water pump	P_{CTP}	$TC_{CTP}=\frac{Q+P_{CH}}{P_{CTP}}$	41.5	41.5	GB 50189–2005 [35]
Cooling tower	P_{CT}	$TC_{CT}=\frac{Q+P_{CH}}{P_{CT}}$	150–200	150–200	GB/T 7190.1–2008 [36]
Fan coil unit	P_{FCU}	$TC_{FCU}=\frac{Q}{P_{FCU}}$	50–60	22	GB/T 19232–2003 [27]; [25]
Fan in outdoor air handling unit	P_{FAN}	$TC_{FAN}=\frac{Q}{P_{FAN}}$	20	/	GB/T 17981–2007 [26]
Outdoor air processor using liquid desiccant	P_{OAP}	$COP_{OAP}=\frac{Q_{OAP}}{P_{OAP}}$	/	4.0	GB/T 27943–2011 [37]
Entire system	$P_{CH}+P_{CWP}+P_{CTP}+P_{CT}+P_{FCU}+P_{FAN}$	$COP_{SYS}=\frac{Q}{P_{CH}+P_{CWP}+P_{CTP}+P_{CT}+P_{FCU}+P_{FAN}}$	3.5–3.7	4.2–4.3 (dry FCUs) 4.7 (radiant terminals)	

Thanks to these improvements and optimizations, the performance of newly designed centrifugal high-temperature water chillers has improved significantly. Table 6 lists the variance in the *COP* of a conventional chiller operating at an outlet chilled water temperature of 7 °C, 16 °C, and 18 °C, and a newly developed chiller operating at relatively high chilled water temperatures (16 °C and 18 °C). When the inlet temperature of the cooling water is 30 °C, the *COP* of the conventional chiller is 5.78, 6.80, and 7.05 with chilled water of 7 °C, 16 °C, and 18 °C, respectively. In other words, the *COP* is 17.6% and 22.0% higher in the 16 °C and 18 °C conditions, respectively, than in the conventional 7 °C chilled water condition. However, the performance of the newly developed chiller is even better: the *COP* is 8.58 and 9.18 with supplied chilled water of 16 °C and 18 °C, respectively. In other words, the *COP* is 48.4% and 58.8% higher in the 16 °C and 18 °C conditions, respectively, compared to the conventional chiller in the 7 °C chilled water condition.

4. Performance analysis of THIC systems

4.1. Performance comparison with conventional systems

Table 7 summarizes the computational formulas and reference values for the energy performance of key components of conventional air-conditioning systems, with FCUs and outdoor air processors under design conditions based on Chinese national performance standards [25–27,34–37]. The reference values for the energy performance of key components of THIC systems are also listed; a centrifugal water chiller is utilized as the high-temperature cooling source, and an outdoor air processor using liquid desiccant (shown in Fig. 6) is selected as the humidity control subsystem. Based on the performance indexes of key components, a performance comparison between THIC systems and conventional systems can be conducted.

According to the energy performance of chillers, chilled water pumps and cooling water pumps, FCUs, and outdoor air handling devices listed in Table 7, if 70% of the building load is extracted by the wet FCUs in the conventional system, the system *COP* under design conditions is 3.5–3.7. Table 7 also gives the *COP* of an entire THIC system; the temperature control subsystem represents half of the total building load. As there may be different sensible terminals for temperature control, Table 7 gives the *COP* of two THIC systems, one adopting dry FCUs and the other adopting radiant terminals. It can be seen that the *COP* values of both THIC systems are higher than 4.0, representing a significant improvement compared to conventional systems. If radiant panels are selected as the sensible terminals, there is no fan power consumption, and the *COP* of the system will be higher. On average, the *COP* of the THIC system with radiant panels is 30% higher than the

conventional system; for the THIC system with dry FCUs, performance improves by about 18%.

4.2. Applications of THIC systems in China

In recent years, THIC systems have gained more and more popularity in China, signifying an important developmental trend for air-conditioning systems in non-residential buildings [38–48]. The variety of applications of THIC systems is growing rapidly, and many non-residential buildings with different functions have adopted THIC systems. For example, a hospital application was introduced by Chen et al. [40], an art exhibition center application by Fan et al. [41], a university office building application by Jin [42], and a museum storeroom application by Zhang et al. [43]. Practical applications of THIC systems have demonstrated their significant superiority to conventional systems in terms of operating costs [44–48]. The following examples are typical applications that have been selected to illustrate the performance of THIC systems.

4.2.1. Application in an office building

Zhao et al. [48] presented the results of a field test of a THIC system in an office building in Shenzhen, China. The building facade is shown in Fig. 9; the application area of the THIC air-conditioning system is about 13,180 m^2. A schematic of this THIC system is shown in Fig. 4(a). High-temperature chilled water produced by a centrifugal chiller is pumped and distributed into dry FCUs and radiant panels to control the indoor temperature. As for indoor humidity control, heat pump-driven liquid desiccant outdoor air handling processors, shown in Fig. 6, are applied in each floor to remove the entire indoor latent load.

Zhao et al. [48] focused on the energy performance of the humidity and temperature control subsystems (the outdoor air conditions were 29.3 °C and 20.3 g/kg). The *COP* values of the outdoor air processors adopted in this building were 4.0–4.4, and the energy efficiency of the humidity control subsystem (COP_{HUM}) was 4.1. The experimental results of the temperature control subsystem in two conditions are listed in Table 8, and it can be seen that the energy efficiency of the temperature control subsystem (COP_{TEMP}) is 3.7 and 4.1 under the two testing conditions. Based on the test results of these two typical operating conditions, it can be concluded that the THIC system in this office building achieved high efficiency, with its total COP_{SYS} higher than 4.0. As the measured *COP* of conventional systems is always lower than 3.0 [49], this THIC system represents a considerable improvement in terms of energy efficiency.

Fig. 9. A THIC air-conditioning system application in Shenzhen (building façade).

Table 8
Performance testing results of the temperature control subsystem [48].

Testing condition	Outdoor condition	Q_{CH} (kW)	COP_{CH}	TC_{CWP}	TC_{CTP}	TC_{CT}	TC_{FCU}	COP_{TEMP}
Condition 1	29.3 °C, 20.3 g/kg	446.1	8.5	14.6	34.2	134.8	18.6	3.7
Condition 2	34.9 °C, 21.6 g/kg	543.4	8.5	18.5	37.7	147	24.4	4.1

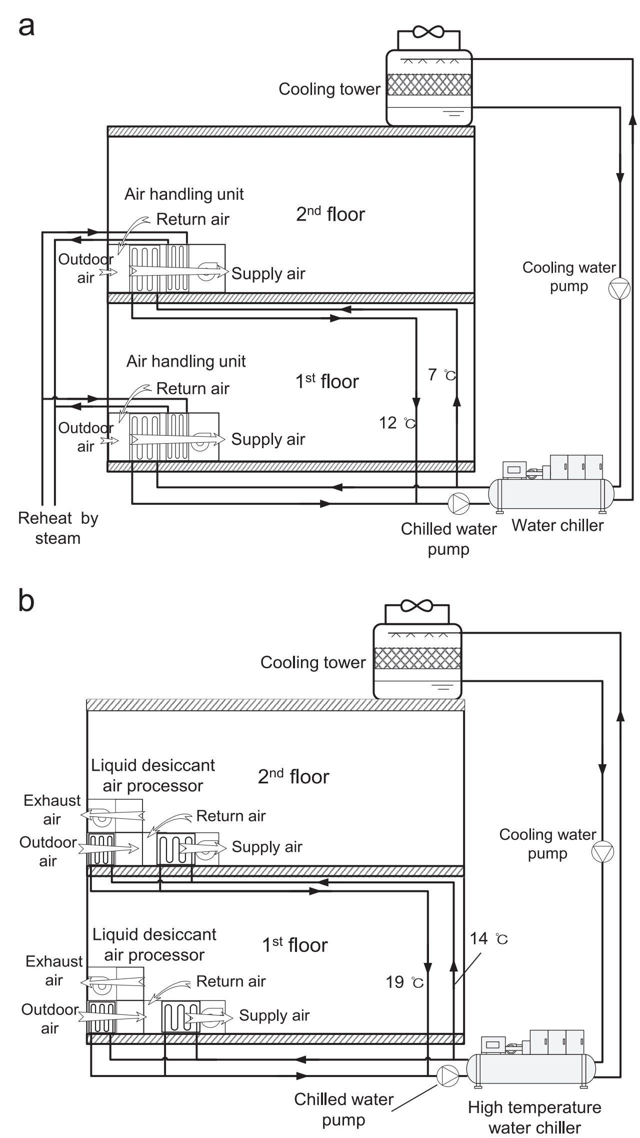


Fig. 10. Transformation of an air-conditioning system in a machine room: (a) the original system; and (b) the existing system.

4.2.2. Application in a workshop

In many industrial applications, THIC air-conditioning systems can provide the appropriate temperature and humidity to satisfy production requirements. Liu et al. [50] analyzed the transformation of an air-conditioning system in a two-floor machine room with an area of about 10,000 m^2. The required indoor temperature and relative humidity for production were 24 ± 2 °C and 55 ± 5%, respectively. The original air-conditioning system was an all-air system with primary return air, as shown in Fig. 10(a). The mixed outdoor air and return air was cooled and dehumidified to the

required humidity ratio by 7 °C supplied chilled water, and then reheated to the required temperature by steam. However, the measured indoor conditions were 21.5–25.5 °C and 46–58% beyond the respective requirements. During operation, insufficient outdoor air was supplied to mitigate the fluctuations of the indoor conditions, which led to worse indoor air quality, and unnecessary energy dissipation occurred between condensing dehumidification and reheating using steam.

In the new THIC system, high-temperature chilled water and liquid desiccant were adopted, as shown in Fig. 10(b). The outdoor air was first pre-cooled by the high-temperature chilled water (14/19 °C) and then dehumidified further by a heat pump-driven liquid desiccant air handling processor. Then, the handled outdoor air was mixed with return air and supplied to the indoor environment after being cooled to an appropriate temperature by the high-temperature chilled water. The indoor parameters measured at different testing points after the transformation indicated that the indoor temperature and relative humidity were both within the allowable range. More importantly, there was no reheat in the transformed system, and the operating cost was less than 50% of the original system's [50].

5. Developmental trends and recommendations for further research

THIC air-conditioning systems are becoming a popular choice for the air-conditioning needs of non-residential buildings. THIC air-conditioning systems satisfy the requirements of indoor temperature and humidity better than conventional systems can, and they represent a significant potential for energy conservation. Although rapid development of THIC systems has taken place in recent ten years, continuous efforts for related research and applications are still needed in the long term. Based on current developments, the following research priorities can be summarized as follows.

5.1. Summarize and refine design methodology of THIC systems

As the air-conditioning method and handling devices in THIC systems are quite different from those in conventional systems, a reasonable scientific design is necessary to ensure proper operation and reduce the operating energy consumption of applications. As various devices can be utilized to construct THIC systems for buildings with different climate conditions or functions, how to choose an appropriate system scheme will continue to be an important puzzle to solve, and the design methodology still needs to be investigated. Many crucial aspects of the design of THIC systems remain unclear, such as the applicable supplied and return temperatures of the high-temperature chilled water for difference compositions of air handling devices, which will be obtained based on entire system optimization.

5.2. Further research on and development of related handling devices

THIC systems provide a new approach to developing air-conditioning devices, and key components such as high-temperature water chillers and dry FCUs have been developed and applied in numerous buildings. However, the performance of existing devices can still be improved, e.g., sensible terminals with high energy efficiency. Standards for dry FCUs [27] and liquid desiccant outdoor air handling processors [37] have already been established in China, and standards for other key devices will be set up in order to guide manufacturers. Nowadays, applications of THIC systems in China are heavily focused on large-scale non-residential buildings, and there are fewer devices suitable for smaller-scale buildings that are being developed. The development of a high-efficiency VRV (Varied Refrigerant Volume) unit specifically for temperature control is one example of a future application of THIC systems.

5.3. Feedback and clarification based on practical operations and applications

The basic task of an air-conditioning system is to regulate indoor temperature and humidity effectively. Finding and solving problems based on practical applications is the best way to improve the performance of THIC systems. Certain details that have previously been neglected or not emphasized in system design might be discovered through implementation and could help to enhance system performance. In practical operation, both daily and annual operating control strategies can be improved; the operating energy performance of key components can be tested, and system efficiency can also be investigated. The feedback between system design and practical applications must be maintained, and both discrepancies and similarities should be taken into account to improve system performance.

6. Conclusions

The THIC system is a new kind of air-conditioning method in which indoor temperature and moisture are regulated separately. In recent years, great improvements have been achieved in terms of theoretical research, equipment development, and applications of THIC systems in China. This paper reviews the development of THIC air-conditioning systems in China, giving detailed descriptions of the progress of key components and the energy performance in demonstrated applications. Compared to conventional systems, THIC systems regulate indoor temperature and humidity better, and they have the potential to save a significant amount of energy because of reduced operating power consumption. Some recommendations for further development of the design methodology, devices, and applications of THIC systems are also mentioned.

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